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MESOPOROUS INORGANIC MATERIALS HAVING CONTROLLED-RELEASE ON-OFF CONTROL FUNCTION, PRODUCTION METHOD THEREOF AND METHOD USING SAME

[0001] This is a Continuation-In-Part of U.S. Appln. No. 10/421,697, filed April 24, 2003, entitled "MESOPOROUS SILICA HAVING CONTROLLED-RELEASE ON-OFF CONTROL FUNCTION, PRODUCTION METHOD THEREOF AND METHOD USING SAME," the disclosure of which is incorporated herein in its entirety by reference.

FIELD OF THE INVENTION

[0002] The present invention relates to a novel mesoporous inorganic materials having a hexagonal pore structure modified with an organic functional group, a production method thereof, and use thereof.

BACKGROUND OF THE INVENTION

[0003] In recent years, incorporating a chemical substance into a solid material and gradually or controllably releasing the chemical substance from the inside to the outside of the solid material, a so-called "controlled release system" or "sustained release system", is regarded as noteworthy. The controlled release system is intended to provide a supply of various chemical substances having different functions in a necessary amount only when needed. The controlled release system is useful in various industrial fields, such as medicines, agricultural chemicals, cosmetics, catalysts, fertilizers and aroma chemicals. In addition to providing efficient use of chemical substances, the controlled release function is directly related to leading-edge technologies, such as technologies for reducing environmental risks (chemical pollution) and technologies for suppressing side effects in medical care (drug delivery system).

[0004] While various techniques have been proposed for a controlled release system, most of them are directed to mixing a chemical substance into a polymer gel or forming a complex consisting of a chemical substance and a polymeric material. These techniques cannot disable the continuous release of a chemical substance, even if they can reduce the rate of the controlled-release of the chemical substance. That is, they cannot provide an on-off control function of controllably releasing a chemical substance in a necessary amount only when needed.

[0005] There have also been proposed some controlled release systems having an on-off control function based on a device using an electrode (Japanese Patent Laid-Open Publication Nos. H 05-269373, H 05-261278, H 05-231560, H 05-221469, H 05-221468 and H 05-212277). Since these systems are essentially provided with a power source, an electrode and an interconnection therebetween, to allow a chemical substance to be controllably released according to an electric field signal, they are not applicable in a specific region where the above interconnection cannot be constructed, for example, within a living body. Thus, there is a need for a controlled release system having an on-off control function in the form of a micro self-sustained system independent of a power source and others.

[0006] Silica (gel) is widely used because it has almost no harm to the environment and living organisms. As one of features, silica has large pores capable of absorbing and incorporating various kinds of chemical substances therein. While it is contemplated to use silica (gel) in a controlled release system in such a manner that a chemical substance incorporated therein is controllably released therefrom, no on-off control function will be attained if silica (gel) is used as it is.

[0007] A technique for providing a controlled-release on-off control function to silica gel or capsule-type silica has been proposed recently (Japanese Patent Laid-Open Publication Nos. 2000-279817, 2001-131249 and 2001-213992). However, an accurate controlled-release control of an incorporated substance cannot be achieved due to uneven size in pores of the silica gel. Thus, there is a need for a material with pores having more uniform outlets or access regions to the outside.

[0008] A material fulfilling the above requirement includes hexagonal mesoporous silica, such as MCM-41, having pores with regularity in diameter and configuration. There is a recent report disclosing a spontaneous-diffusion controlled-release property of a drug incorporated in MCM-41 (M. Vallet-Regi et al, Chem. Mater. Vol. 13, p 308, 2001; B. Munoz et al., Chem. Mater. Vol. 15, p 500, 2003). This report includes no description of controlled-release on-off control.

SUMMARY OF THE INVENTION

[0009] In view of the above circumstances, it is a primary object of the present invention to provide a mesoporous silica having a hexagonal structure, capable of controllably releasing a substance incorporated therein, and a production method thereof.

[0010] The inventor found that a functional substance could be confined in the pores of a hexagonal mesoporous silica by introducing a dimerizable organic functional group at the entrances of the pores and dimerizing the functional group. The incorporated substance could be released when needed by splitting the dimerized functional group. Based on this knowledge, the inventor has finally accomplished the present invention.

[0011] According to a first aspect of the present invention, there is provided a mesoporous silica having a hexagonal structure. This mesoporous silica comprises an organic

functional group provided at the entrances of the pores thereof. The organic functional group is dimerizable in response to light.

[0012] In a first embodiment of the mesoporous silica set forth in the first aspect of the present invention, the organic functional group may be an α, β-unsaturated ketone moiety.

[0013] In a second embodiment of the mesoporous silica set forth in the first aspect of the present invention, the organic functional group may be reversibly dimerizable in response to light.

[0014] In a third embodiment of the mesoporous silica set forth in the first aspect of the present invention, the organic functional group may be derived from a coumarin derivative.

[0015] According to a second aspect of the present invention, there is provided a mesoporous silica having a hexagonal structure. This mesoporous silica comprises a functional substance filled in the pores thereof, and a dimerized organic functional group provided at the entrances of the pores to close the entrances.

[0016] In a first embodiment of the mesoporous silica set forth in the second aspect of the present invention, the organic functional group may be α, β-unsaturated ketone moiety.

[0017] In a second embodiment of the mesoporous silica set forth in the second aspect of the present invention, the organic functional group may be reversibly dimerizable in response to light.

[0018] In a third embodiment of the mesoporous silica set forth in the second aspect of the present invention, the organic functional group may be derived from a coumarin derivative.

[0019] According to a third aspect of the present invention, there is provided a method of producing a mesoporous silica, comprising the steps of (1) preparing a mesoporous silica having a hexagonal structure by use of a template comprising a surfactant capable of

forming a hexagonal structure in an aqueous solution, (2) introducing an organic functional group, which is dimerizable in response to light, to the mesoporous silica having a hexagonal structure while leaving the surfactant in the pores of the mesoporous silica, and (3) then removing the surfactant contained in the mesoporous silica with a solvent.

[0020] This method may further include the step of subjecting the mesoporous silica to acid treatment between the preparing step (1) and the introducing step (2).

[0021] According to a fourth aspect of the present invention, there is provided a method of producing a mesoporous silica, comprising the steps of (1) preparing a mesoporous silica having a hexagonal structure by use of a template comprising a surfactant capable of forming a hexagonal structure in an aqueous solution, (2) introducing an organic functional group, which is dimerizable in response to light, to the mesoporous silica having a hexagonal structure while leaving the surfactant in the pores of the mesoporous silica, (3) removing the surfactant contained in the mesoporous silica with a solvent, (4) filling the pores of the mesoporous silica with a functional substance, and (5) dimerizing the organic functional group with light.

[0022] This method may further include the step of subjecting the mesoporous silica to acid treatment between the preparing step (1) and the introducing step (2).

[0023] According to a fifth aspect of the present invention, there is provided a method of removing a chemical substance, comprising the steps of preparing the mesoporous silica set forth in the first aspect of the present invention, incorporating the chemical substance into the pores of the mesoporous silica, and dimerizing the organic functional group with light.

[0024] According to a sixth aspect of the present invention, there is provided a method of controlling the release of a functional substance, comprising the steps of preparing the

mesoporous silica set forth in the second aspect of the present invention, and splitting the dimerized organic functional group to allow the functional substance to be released from the pores.

[0025] According to a seventh aspect of the present invention, there is provided a method of controlling the release of a functional substance, comprising the steps of preparing the mesoporous silica set forth in the second embodiment of the second aspect of the present invention, and irradiating the mesoporous silica with a light having a wavelength causing the split of the dimerized organic functional group to allow the functional substance to be released from the pores.

[0026] According to an eighth aspect of the present invention, there is provided a method of controlling the release of a functional substance, comprising the steps of preparing the mesoporous silica set forth in the second embodiment of the second aspect of the present invention, irradiating the mesoporous silica with a light having a wavelength causing the split of the dimerized organic functional group to allow the functional substance to be released from the pores, and irradiating the mesoporous silica with a light having a wavelength causing dimerization of the organic functional group to allow the release of the functional substance to be discontinued.

[0027] According to a ninth aspect of the present invention there is provided a mesoporous inorganic material having an ordered array structure of a plurality of one-dimensional pores, wherein the entrances of the pores have a functional group capable of forming a bond based on a chemical reaction in response to an external stimulus.

[0028] The mesoporous inorganic material set forth in the ninth aspect of the present invention may be one selected from the group consisting of silica, titania, zirconia, alumina,

silica-alumina, silica-titania, tin phosphate, niobium phosphate, aluminum phosphate, titanium phosphate, and the oxides, nitrides, sulfides, selenides, tellurides, composite oxides and composite salts thereof.

[0029] In the mesoporous inorganic material set forth in the ninth aspect of the present invention, the external stimulus may be at least one selected from the group consisting of light, heat, a radioactive ray, an acid, an alkali, a crosslinking agent, magnetism and an ion.

[0030] In the mesoporous inorganic material set forth in the ninth aspect of the present invention, the chemical reaction may be at least one selected from the group consisting of a dimerization reaction, a multimerization reaction, a polymerization reaction, a condensation reaction, an addition reaction and a complex-formation reaction.

[0031] In the mesoporous inorganic material set forth in the ninth aspect of the present invention, the functional group may be at least one selected from the group consisting of an unsaturated group, a carboxyl group, a hydroxyl group, an amino group, an amide group, an ether group, an ester group, a carbamate group and a silane group.

[0032] The mesoporous inorganic material set forth in the ninth aspect of the present invention may include a functional substance filled in the pores, wherein the entrances of the pores are closed by means of the formation of the bond in the functional group.

[0033] The functional substance may be at least one selected from the group consisting of a steroid compound, a vitamin compound, a hormone compound, a pharmacologically active compound, a pesticidal compound, a physiologically active compound, an amino acid compound, a saccharide compound, a fatty acid compound and a nucleic acid compound.

[0034] According to a tenth aspect of the present invention there is provided a method of producing a mesoporous inorganic material which has pores filled with a functional

substance, comprising the steps of (1) preparing a mesoporous inorganic material having an ordered array structure of a plurality of one-dimensional pores by use of a template comprising a surfactant in an aqueous solution, (2) introducing an organic functional group capable of forming a bond based on a chemical reaction in response to an external stimulus, to the entrances of the pores of the mesoporous inorganic material while leaving the surfactant in the pores of the mesoporous inorganic material, (3) removing the surfactant, (4) filling the pores of the mesoporous inorganic material with a functional substance, and (5) applying the external stimulus to the mesoporous inorganic material to form the bond in the organic functional group based on the chemical reaction.

[0035] According to an eleventh aspect of the present invention there is provided a method of incorporating and/or removing a chemical substance, comprising the steps of: preparing a mesoporous inorganic material having an ordered array structure of a plurality of one-dimensional pores, wherein the entrances of the pores have a functional group capable of forming a bond based on a chemical reaction in response to an external stimulus; incorporating a chemical substance in the pores; and applying the external stimulus to the mesoporous inorganic material to form a bond in the functional group.

[0036] According to the present invention, the functional group capable of forming a bond or splitting the bond in response to an external stimulus is introduced to the entrances of the pores of the mesoporous inorganic material having an ordered array structure of one-dimensional pores to provide a function of opening/closing the pores of the mesoporous inorganic material. Thus, the mesoporous inorganic material of the present invention can controllably confine a specific material therein and release the specific material therefrom. Specifically, the conditions of the external stimulate can be changed to open or close the

pores of the mesoporous inorganic material. This opening/closing function makes it possible to absorb or incorporate a harmful or desired chemical substance, or to controllably release a functional substance filled in the pores.

[0037] The mesoporous inorganic material of the present invention has a function of incorporating a functional chemical substance in its solid material and gradually or controllably releasing the functional chemical substance from the inside to the outside of the solid material. Thus, this function can be utilized in various fields (e.g. pharmaceutical, pesticidal, cosmetic, catalytic, manurial or aroma chemical field) to supply a desired amount of the functional chemical substance when needed depending on circumstances.

[0038] For example, it is contemplated that the mesoporous inorganic material of the present invention is used in combination with an odor sensor of ambient air to controllably release an incorporated aromatic compound to the outside in response to the detection of odor so as to maintain comfortable ambient air, or to apply agricultural chemicals in response to the arrival of harmful insects. It is also contemplated to use the present invention as a drug delivery system, in such a manner that a mesoporous silica incorporating a drug therein is injected into a human body, and then only an affected area is irradiated with ultraviolet light to allow the drug to be released and to act only in the affected area. It is also expected to use the present invention in such a manner that when the concentration of a chemical substance in surrounding air increases up to a given value, a dimerized functional group is split so as to absorb the chemical substance into the pores thereof, thereby removing the chemical substance from the surrounding air.

[0039] As described above, the mesoporous inorganic material of the present invention can provide excellent technical means applicable to various fields.

DESCRIPTION OF THE PREFERRED EMBODIMENT

[0040] The present invention is directed to a hexagonal mesoporous silica, i.e., a mesoporous silica having a hexagonal structure. The mesoporous silica essentially comprises a dimerizable organic functional group provided at the entrances of the pores thereof. The organic functional group is dimerizable in response to light, i.e., photo-dimerizable.

[0041] The mesoporous silica can be obtained through a method comprising the steps of preparing a mesoporous silica having a hexagonal structure by use of a template comprising a surfactant capable of forming a hexagonal structure in an aqueous solution, introducing an organic functional group, which is dimerizable in response to light, at the entrances of the pores of the mesoporous silica having a hexagonal structure, and then removing the surfactant contained in the mesoporous silica with a solvent.

[0042] The present invention is also directed to a hexagonal mesoporous silica comprising a functional substance filled in the pores thereof and a photo-dimerized organic functional group provided at the entrances of the pores to close the entrances.

[0043] The mesoporous silica including a functional substance filled in the pores can be obtained by adding the steps of filling the pores of the mesoporous silica with the functional substance and dimerizing the organic functional group with light, after the step of removing the surfactant in the above method.

[0044] The present invention is further directed to a mesoporous inorganic material having an ordered array of one-dimensional pores filled with a functional substance.

[0045] The mesoporous inorganic material may be prepared by use of a template comprising a surfactant capable of forming an ordered porous structure.

INORGANIC MATERIAL

[0046] In the present invention, any suitable inorganic material may be used. Examples for the inorganic material include silica, titania, zirconia, alumina, silica-alumina, silica-titania, tin phosphate, niobium phosphate, aluminum phosphate, titanium phosphate, and the oxides, nitrides, sulfides, selenides, tellurides, composite oxides and composite salts thereof.

FUNCTIONAL GROUP

[0047] The functional group to be provided at the entrances of the pores of the mesoporous inorganic material of the present invention may be, but not limited to, any suitable functional group capable of forming a bond based on a chemical reaction in response to an external stimulus.

[0048] The phrase "bond based on a chemical reaction in response to an external stimulus" herein means a reversible or irreversible bond, which is capable of being formed and split depending on the conditions of the external stimulus. In particular, the functional group may be one capable of being changed between dimer and monomer in response to light irradiation. The functional group may also be one capable of forming a bond and splitting the bond based on oxidation/reduction reactions.

[0049] The functional group capable of forming a reversible bond is preferably used as a material for temporarily storing a functional substance in the pores. The functional group capable of forming an irreversible bond is also preferably used as a material for semi-permanently storing a functional substance in the pores.

[0050] The external stimulus may include, but is not limited to, light, heat, a radioactive ray, an acid, an alkali, a crosslinking agent, magnetism and an ion. Each of these external stimuli may be applied by means of light irradiation, heating/cooling, radiation, change of

pH value, addition of an acid and/or an alkali, change of coexisting ions, change of coexisting chemical substances or change of an external magnetic field.

[0051] The chemical reaction may include, but is not limited to, a dimerization reaction, a multimerization reaction, a polymerization reaction, a condensation reaction, an addition reaction and a complex-formation reaction. In particular, the chemical reaction may be a dimerization reaction to be caused by light irradiation.

[0052] The bonding mechanism may include, but is not limited to, hydrogen bond, ionic bond, covalent bond, coordinate bond and van der Waals bond.

[0053] The functional group capable of forming the bond in response to the external stimulus may include an unsaturated group, a carboxyl group, a hydroxyl group, an amino group, an amide group, an ether group, an ester group, a carbamate group and a silane group. Examples for the unsaturated group may include a vinyl group and an α, β-unsaturated ketone group. Examples for the ether group may include – O – R, wherein R is an alkyl group having 1 to 6 carbon atoms. Examples for the ester group may include – COOR, wherein R is an alkyl group having 1 to 6 carbon atoms. In particular, the functional group may be an α, β-unsaturated ketone group derived from a coumarin derivative.

[0054] The bond to be formed by these functional groups may include a carbon-carbon bond, an ester bond, an amide bond, an acetal bond and a carbamate bond.

[I] PREPARATION OF HEXAGONAL MESOPOROUS SILICA WITH TEMPLATE SURFACTANT

[0055] A crude product of a hexagonal mesoporous silica may be prepared by use of a template comprising a surfactant, prior to removing the template (This method has already

been reported in U.S. Patent Number 5,143,879, issued Sep. 1, 1992). This crude product can be obtained through any suitable conventional method, for example, using a silica source and a surfactant capable of forming a hexagonal structure in an aqueous solution, as raw materials.

[0056] While the surfactant herein may be a typical surfactant for use in a conventional production process for a mesoporous silica having a hexagonal pore arrangement, the present invention is not limited to a specific surfactant. Any other suitable surfactant capable of forming a hexagonal structure in an aqueous solution may be used. Examples for the surfactant include: aliphatic quaternary ammonium salts, such as hexadecyltrimethylammonium bromide, hexadecyltrimethylammonium chloride, octadecyltrimethylammonium bromide, decyltrimethylammonium bromide, dodecyltrimethylammonium bromide and hexadecyldimethylethylammonium bromide; aliphatic amine salts, such as hexadecylamine; and alkyl sulfates, such as sodium dodecyl sulfate.

[0057] While the silica source herein may be a typical silica source for use in a conventional production process for a mesoporous silica having a hexagonal pore arrangement, the present invention is not limited to a specific silica source. Any other suitable silica source capable of being formed into a mesoporous silica having a hexagonal pore arrangement may be used. For example, the silica source includes sodium silicate, potassium silicate, calcium silicate, tetraethoxysilane, tetramethoxysilane, and tetra-n-propoxysilane.

[0058] Both the surfactant and the silica source are used in the form of an aqueous solution. These aqueous solutions are prepared individually.

[0059] While the concentration of the surfactant in the aqueous solution may be set at any appropriate value depending on the type of the surfactant, it is typically about 0.2 to 2 M.

[0060] Alkaline compounds, such as sodium hydroxide, potassium hydroxide, or tetramethylammonium hydroxide, may be added to the surfactant aqueous solution when needed. When added, the amount of alkaline compounds is preferably about 1 to 1.5 molar equivalents with respect to the surfactant.

[0061] The concentration of the silica source in the aqueous solution is typically, but not limited to, about 0.5 to 4 M.

[0062] These aqueous solutions are mixed by stirring, at a temperature of about 25°C to 40°C, for about 0.5 to 5 hours.

[0063] While the mixing ratio of the surfactant aqueous solution (vol) : the silica-source aqueous solution (vol) may be typically set at 1 : 0.5 to 1 : 2, the present invention is not limited to such a specific value. Any other suitable mixing ratio allowing the hexagonal structure formed of the template surfactant to be filled with the silica source, may be selected.

[0064] Then, an inorganic acid such as sulfuric acid, nitric acid, hydrochloric acid, or hypochlorous acid, is added to the mixed solution to set the pH of the mixed solution at about 9 to 12, preferably about 10 to 11. The resulting solution is stirred at a temperature of about 25°C to 80°C for about 0.5 to 6 hours. While the concentration of the inorganic acid to be added may be set at about 0.5 to 4 M, preferably about 1 to 3 M, and the amount of the inorganic acid to be added may be set at about 20 to 100 mL, preferably about 50 to 70 mL, per 100 mL of the mixed solution of the surfactant and the silica source, the present

invention is not limited to such a specific value. Any other suitable value allowing the pH of the mixed solution to be set approximately in the above desired range, may be selected.

[0065] After a precipitate is formed, it is filtered and rinsed with water. Then, the precipitate is dried at a temperature of about 80 to 130°C, preferably about 90 to 110°C, for about 10 to 40 hours, preferably about 12 to 26 hours, to obtain a hexagonal mesoporous silica with the template surfactant.

[0066] After the formation of the above precipitate, the precipitate may be directly filtered and dried. Alternatively, the precipitate may be subjected to acid treatment before the filtration.

[0067] The acid treatment may be carried out in the following method.

[0068] The mixed solution containing the precipitate is first left at a temperature of about 80 to 120°C for 20 to 30 hours. Then, a neutral salt (e.g. sodium chloride, potassium chloride, lithium chloride, sodium bromide, potassium bromide, sodium iodide, or potassium iodide) is added to the mixed solution at about 60 to 90 mol%, preferably about 70 to 80 mol% on the basis of 100% of silica atoms contained in the silica source. Prior to the addition, the salt is preferably dissolved in a small amount of water.

[0069] Then, an inorganic acid (such as sulfuric acid, nitric acid, hydrochloric acid, and hypochlorous acid) is added to the mixed solution to set the pH of the mixed solution at about 9 to 12, preferably about 10 to 11. While the concentration of the inorganic acid may be set at about 0.5 to 4 M, preferably about 1 to 3 M, the present invention is not limited to such a specific value. Any other suitable value allowing the pH of the mixed solution to be set in the above desired range, may be selected.

[0070] Following the addition of the inorganic acid, the mixed solution containing a precipitate formed therein is left at a temperature of about 80 to 120°C for 20 to 30 hours.

[0071] The above acid treatment, i.e., the operation of adding an inorganic acid to the mixed solution to set the pH thereof at about 9 to 12, preferably 10 to 11, and leaving the mixed solution containing the precipitate at a temperature of about 80 to 120°C for 20 to 30 hours, may be repeated. In this case, no salts may be added on and after the second operation.

[0072] While the acid treatment may be repeated for any number of times, it is typically 1 to 5 times, preferably 2 to 3 times.

[0073] After completion of the acid treatment(s), the resulting precipitate may be filtered and dried in the same way as described above. The acid treatment provides the hexagonal mesoporous silica with enhanced heat stability.

[0074] In this manner, the mesoporous silica having a hexagonal pore arrangement can be obtained. At this moment, the surfactant remains in the pores of the mesoporous silica. If a dimerizable organic functional group is introduced to the mesoporous silica while the surfactant is still in the pores thereof, the dimerizable organic functional group never enters into the pores, and a mesoporous silica having an excellent controlled release function can be obtained.

[II] INTRODUCTION OF DIMERIZABLE ORGANIC FUNCTIONAL GROUP

[0075] In order to introduce an organic functional group which is dimerizable in response to light (hereinafter sometimes referred to as "dimerizable functional group") to the mesoporous silica, a compound having a dimerizable functional group (hereinafter sometimes referred to as "dimerizable compound") is used. This compound may be

reversibly or irreversibly dimerizable in response to light irradiation such as ultraviolet irradiation, preferably reversibly dimerizable in response to light irradiation.

[0076] The dimerizable compound may be an α, β-unsaturated ketone. Specifically, the compound having the organic functional group reversibly dimerizable in response to light irradiation may be a coumarin derivative having at least one substituent, preferably one or two substituents, such as a hydroxyl, amino, carboxyl or ester group [e.g. -CO-OR^1 (R^1 may be an alkyl group having about 1 to 6 carbon atoms)]. Examples of the reversibly dimerizable compound include 7-hydroxy coumarin, 3, 4-dihydroxy coumarin, 4-hydroxy coumarin, and 7-amino-4-methylcoumarin.

[0077] The compound having an organic functional group irreversibly dimerizable in response to light radiation may be chalcones having at least one substituent, preferably one or two substituents, such as a hydroxyl, amino, carboxyl or ester group [e.g. -CO-OR^1 (R^1 may be an alkyl group having about 1 to 6 carbon atoms)]. Examples of the irreversibly dimerizable compound include 4-hydroxy chalcone, 4'-hydroxy chalcone, and 4, 4'-dihydroxy chalcone.

[0078] In order to allow a dimerizable compound to be introduced to a mesoporous silica, an olefin group may be introduced to the dimerizable compound, which then reacts with hydrosilanes to synthesize a silane compound containing a dimerizable group.

[0079] An olefin group can be introduced to a dimerizable compound, for example, by reacting an organic halide having an olefin group with a functional group such as the hydroxyl group of the dimerizable compound in a usual manner, for example, in a solvent and/or in the presence of a base. The organic halide having an olefin group may be, but not limited to, allyl chloride, allyl bromide, allyl iodide, 3-bromocyclohexene, or 6-bromo-1-

hexene, which has about 3 to 8 carbon atoms. The kind (the number of carbon atoms) of the organic halide having an olefin group may be appropriately selected depending on the kind of the compound having a dimerizable organic group, to allow the dimerizable compound to close the entrances of the pores of the mesoporous silica when dimerized.

[0080] Examples for the solvent may include acetone, methyl ethyl ketone, dimethylformamide, dimethylsulfoxide, tetrahydrofuran, and 1, 4-dioxane. A particularly preferable solvent is acetone. Examples for the base may include sodium carbonate, potassium carbonate, potassium bicarbonate, sodium bicarbonate, sodium hydroxide, potassium hydroxide, potassium hydroxide, cesium carbonate, sodium methoxide, and potassium-t-butoxide. The amount of the base to be used may be 1 to 3 molar equivalents with respect to a dimerizable compound such as 7-hydroxycoumarin. The reaction temperature may be about 40 to 100°C, preferably 60 to 80°C. The reaction time may be about 3 to 24 hours.

[0081] The obtained olefin-containing dimerizable compound is reacted with an alkoxysilane in a usual manner to provide a silane compound containing a dimerizable group. While the alkoxysilane to be used herein may be a compound having at least one alkoxy group, preferably alkoxysilane represented by $HSiR_3$ (in this formula, R may be the same or different, and represents an alkyl group having about 1 to 4 carbon atoms or an alkoxy group having about 1 to 3 carbon atoms, wherein at least one of R is an alkoxy group having 1 to 3 carbon atoms), the present invention is not limited to such a compound. Any other suitable compound capable of reacting with a silanol group of the hexagonal mesoporous silica to introduce a dimerizable functional group to the hexagonal mesoporous

silica, may be used. Specifically, the alkoxysilane may include triethoxysilane, trimethoxysilane, diethoxymethylsilane, and ethoxydimethylsilane.

[0082] The above reaction may be conducted in the presence of a solvent and/or a catalyst. Examples for the solvent may include toluene, xylene, tetrahydrofuran, dioxane, benzene, hexane, dichloromethane, and chloroform. A particularly preferable solvent is toluene or xylene. The amount of the dimerizable compound to be used is preferably about 1 to 1.5 molar equivalents, more preferably about 1 to 1.2 molar equivalents, with respect to the alkoxysilane. Examples for the catalyst may include: a platinum catalyst, such as platinum-1,3-divinyl-1,1,3,3- tetramethyldisiloxane complex, platinum-2,4,6,8-tetramethyl-2,4,6,8-tetravinyl- cyclotetrasiloxane complex, chloroplatinic acid, activated carbon-bearing platinum, and alumina-bearing platinum; a rhodium catalyst, such as Wilkinson's complex ($RhCl(PPh_3)_3$), activated carbon-bearing rhodium, and alumina-bearing rhodium; and a palladium catalyst, such as tetrakistriphenylphosphine palladium, and activated carbon-bearing palladium. The amount of the catalyst to be used may be about 0.005 to 0.5 mol%, preferably about 0.02 to 0.1 mol% with respect to the alkoxysilane. The reaction temperature may be about 0 to 80°C, preferably about 25°C to 30°C. The reaction time-period may be about 10 minutes to 4 hours.

[0083] The obtained dimerizable-group-containing silane compound is introduced to the hexagonal mesoporous silica having the template surfactant filled in the pores thereof, instead of the hexagonal mesoporous silica from which the template surfactant has been removed through calcination or extraction. The template surfactant filled in the pores allows the dimerizable-group-containing silane compound to be introduced to the

hexagonal mesoporous silica in such a manner that it reacts with only the silanol groups at the entrances of the pores without entering into the pores.

[0084] The dimerizable functional group can be introduced to the pore entrances of the mesoporous silica by suspending the hexagonal mesoporous silica in a solvent (e.g. n-hexane, or toluene), and then adding a dimerizable-group-containing silane compound to react with the hexagonal mesoporous silica at a temperature of about 25°C to 80°C for about 10 minutes to 6 hours.

[0085] While the amount of the dimerizable-group-containing silane compound to be used may be typically about 2 to 20 weight parts on the basis of 100 weight parts of the mesoporous silica filled with the temperate surfactant, the present invention is not limited to such a specific value. Any other suitable value allowing the silane compound to confine the functional substance to be incorporated into (filled in) the pores of the hexagonal mesoporous silica when dimerized after the introduction, may be selected.

[0086] In addition, the photo-dimerizable functional group may be introduced to the hexagonal mesoporous silica so as to form a bond capable of being readily split, such as an ester bond, an amide bond or a disulfide bond, by a reaction between the silanol group at the pore entrances of the hexagonal mesoporous silica and the dimerizable functional group through a suitable conventional method depending on the kind of the photo-dimerizable compound. In this case, the dimerized functional group may be split through an appropriate method such as acid treatment or a reduction reaction.

[0087] Besides the dimerizable functional group, any suitable crosslinkable functional group, such as an ester group or an amino group, may be introduced to the entrances of the pores of the mesoporous inorganic material with a one-dimensional porous structure by

means of a conventional reaction, to form a readily splitable bond, such as an ester bond, an amide bond or an acetal bond. In this case, the bond can be split through an appropriate method to incorporate or absorb a chemical substance, or to controllably release a functional substance.

[III] REMOVAL OF SURFACTANT

[0088] After the introduction of the dimerizable functional group to the mesoporous silica, the surfactant remaining in the pores is removed with a solvent. If the remaining surfactant is removed through a calcination treatment, the introduced dimerizable functional group will also be eliminated. Thus, in the method of the present invention, it is essential to remove the remaining surfactant with a solvent.

[0089] The surfactant is preferably removed, but not limited to, through an extraction-method using an alcohol capable of adequately dissolving the surfactant, e.g. aliphatic alcohol, such as methanol or ethanol. When an alcohol is used, the surfactant is preferably removed with a mixture of hydrochloric acid and the alcohol. When hydrochloric acid is used, the concentration of the hydrochloric acid in the mixture is preferably, but not limited to, about 0.5 to 5 M.

[0090] In the mesoporous silica with a hexagonal structure obtained in this manner, the mesoporous silica having a dimerizable organic functional group at the pore entrances is also within the scope of the present invention.

[0091] The term "dimerizable organic functional group" in the mesoporous silica means that the organic functional group has not been dimerized yet, and the pore entrances of the mesoporous silica are still open. The term also means that the organic functional group has been introduced to the pore entrances of the mesoporous silica, but not substantially

introduced into or to the inside of the pores. More specifically, the term means that the dimerizable organic functional group has been introduced to a position of the mesoporous silica where the functional group can close the pore entrances when dimerized.

[IV] FILLING OF FUNCTIONAL SUBSTANCE AND DIMERIZATION OF DIMERIZABLE FUNCTIONAL GROUP

[0092] In the dimerizable functional group-introduced mesoporous silica synthesized as above, the functional group can be dimerized to cover and close the pore entrances of the mesoporous silica.

[0093] The dimerization can be caused by irradiation of the mesoporous silica with light, such as ultraviolet light having a wavelength depending on the kind of the functional group. The irradiation time may be appropriately set depending on the amount of the functional group to be dimerized. For example, it may be set in accordance with the measurement of the absorption peak of the dimerizable functional group.

[0094] When a reversibly photo-dimerizable group such as a coumarin derivative is introduced as a dimerizable compound, the dimerization can be typically caused by irradiating the mesoporous silica with ultraviolet light having a wavelength of 310 nm or more, particularly, about 320 nm to 340 nm. While a lamp to be used herein is preferably a high-pressure mercury lamp, the present invention is not limited to such a specific lamp, but any other suitable lamp capable of radiating ultraviolet light having a wavelength of 310 nm or more. When a high-pressure mercury lamp is used, light components having a wavelength of less than 310 nm can be removed by radiating light through a heat-resistant hard glass jacket.

[0095] When a coumarin derivative is used as a dimerizable functional group, the dimerized functional group can be split and monomerized by irradiating the mesoporous silica with ultraviolet light having a wavelength of about 250 nm (e.g. about 240 to 260 nm). The ultraviolet light of this wavelength can be radiated by using a low-pressure mercury lamp together with a silica or quartz glass housing.

[0096] This reversible change can be determined by measuring the presence of an ultraviolet absorption (absorption at about 310 to 330 nm when the photo-dimerizable group is a coumarin derivative) in an ultraviolet spectrum of the photo-dimerizable group.

[0097] The dimerization/monomerization reactions of reversibly dimerizable group such as coumarin derivatives can be utilized to on-off control the function of controllably releasing a functional substance incorporated in the pores of the mesoporous silica to the outside of the pores. Specifically, a functional substance can be released in any desired place at any desired amount by irradiating the mesoporous silica with light having a wavelength causing the split of dimerized organic functional group to allow the functional substance to be released to the outside of the pores and with light having a wavelength causing the dimerization of the organic functional group to allow the release of the functional substance to be discontinued. Further, the above on-off control can be repeated.

[0098] When the dimerized group cannot be split by light, it may be split by other means depending on the type of the bond between the group and the mesoporous silica. For example, an ester bond or an amide bond can be split through a hydrolysis reaction using an acid or the like, or a reduction reaction to allow the functional substance to be released to the outside of the pores. Thus, even if the group is associated with the mesoporous silica

through an irreversible bond, the release of the functional substance confined in the pores can be on-off controlled at any desired place or when needed.

[0099] Any functional substance capable of getting into the pores may be used as the substance to be filled in the pores of the mesoporous silica, according to intended purposes. For example, the functional substance may include: a steroid compound, such as cholestane, cholesterol, progesterone, testosterone or estradiol; a vitamin compound, such as vitamin A or vitamin B; a hormone compound, such as adrenalin or noradrenalin; a pharmacologically active compound, such as penicillin or ibuprofen; a pesticidal compound, such as phosphate esters; a physiologically active compound, such as alkaloid or prostaglandin; an amino acid including oligopeptide; a saccharide including monosaccharide and polysaccharide; a fatty acid including fat; and a nucleic acid including oligonucleotide.

[00100] A method of filling the functional substance in the pores can be appropriately selected in consideration of the kind of the functional substance and other factors. For example, the mesoporous silica of the present invention having the un-dimerized functional group (off state) may be immersed into a liquid containing a functional substance to introduce the functional substance into the pores, and then the functional group may be dimerized to close the pore entrances.

[00101] The filling method will be described in more detail below in connection with a specific example in which a coumarin derivative is used as the dimerizable group, and cholestane, a steroid, is used as the functional substance.

[00102] [0072] A mesoporous silica modified with the organic functional group consisting of a coumarin derivative is immersed (for about 24 hours) in an n-hexane

solution containing cholestane (the concentration of cholestane and the amount of the solution are not limited to a specific value). Then, the mesoporous silica is filtered and sufficiently rinsed with n-hexane. The mesoporous silica containing cholestane is irradiated with ultraviolet light from a high-pressure mercury lamp through a heat-resistant hard glass jacket to remove the light having a wavelength of less than 310 nm. The irradiation time may be appropriately set according to the amount of the mesoporous silica. The irradiation is continued until there shows no reduction in absorption of the photo-dimerizable group in a measured ultraviolet spectrum.

[00103] The mesoporous silica can be irradiated with ultraviolet light of about 250 nm wavelength from a low-pressure mercury lamp with a silica glass housing to split the dimerized functional group and controllably release the functional substance. In this case, the irradiation time may be appropriately set according to the amount of the functional substance (cholestane) to be controllably released to allow the irradiation to be discontinued when there shows no increase in absorption of the photo-dimerizable group in a measured ultraviolet spectrum.

[00104] The mesoporous silica of the present invention has a function of incorporating a functional substance in its solid body and controllably releasing the functional substance from the inside to the outside of the solid body. That is, the mesoporous silica of the present invention has a function of supplying a functional substance in a desired amount only when needed according to circumstances. The mesoporous silica of the present invention can be used in various fields (e.g. medicines, agricultural chemicals, cosmetics, catalysts, fertilizers and aroma chemicals). For example, it is contemplated that the mesoporous silica of the present invention is used in combination

with an odor sensor of ambient air to controllably release an incorporated aromatic compound to the outside in response to the detection of odor so as to maintain comfortable ambient air, or to apply agricultural chemicals in response to the arrival of harmful insects. It is also contemplated to use the present invention as a drug delivery system in such a manner that a mesoporous silica incorporating a drug therein is injected into a human body, and then only an affected area is irradiated with ultraviolet light to allow the drug to be released and to act only in the affected area. It is also expected to use the present invention in such a manner that when the concentration of a chemical substance in surrounding air increases up to a given value, a dimerized functional group is split so as to absorb the chemical substance into the pores thereof to remove the chemical substance from the surrounding air.

[00105] As described above, the present invention provides a hexagonal mesoporous silica modified with an organic functional group reversibly or irreversibly dimerizable in response to light irradiation such as ultraviolet irradiation. This mesoporous silica allows the functional substance incorporated in the pores thereof to be controllably diffused to the outside of the pores in response to ultraviolet irradiation or the like.

[00106] While the present invention will be more specifically described below in conjunction with Examples, it is not limited thereto.

[EXAMPLE 1]

SYNTHESIS OF HEXAGONAL MESOPOROUS SILICA

(CONTAINING TEMPLATE SURFACTANT)

[00107] 22.86 g of sodium silicate (silicon: 0.20 mol; sodium: 0.184 mol) was completely dissolved in 100 g of water. 48.86 g of tetramethylammonium hydroxide

(0.134 mol) and 38.72 g of hexadecyltrimethylammonium bromide (0.102 mol) were added to another 100 g of water, and completely dissolved therein by heating them up to 35°C. The two homogenous aqueous solutions were mixed together, and sufficiently stirred at about 25°C for 2 hours.

[00108] Then, 13.28 g of sulfuric acid (0.13 mol) dissolved in 51 g of water was slowly added to the above solution, and the obtained mixed solution was stirred at about 25°C for 2 hours to form a precipitate. The solution part of the mixed solution had a pH of about 10.5. The mixed solution was transferred into a polypropylene bottle, and left at 100°C for 24 hours. After the mixed solution was cooled down to about 25°C, concentrated sulfuric acid was added thereto until the pH became about 10.5. Then, 11.83 g of potassium chloride (0.15 mol) was added thereto, and the obtained solution was left at 100°C for 24 hours. After that, concentrated sulfuric acid was added again to adjust the pH to about 10.5. The precipitate formed was filtered, and sufficiently rinsed with distilled water. Then, the precipitate was dried at 105°C for 24 hours. In this manner, a hexagonal mesoporous silica containing a template surfactant was synthesized with a stable structure.

(2) SYNTHESIS OF 7-ALLYLOXYCOUMARIN

[00109] 4.15 g (30 mmol) of potassium carbonate anhydride (insoluble) and subsequently, 6.05 g (50 mmol) of allyl bromide were added to an acetone solution (100 mL) containing 3.24 g of commercially available 7-hydroxycoumarin (20 mmol). The obtained solution was reacted at 70°C for 12 hours. After filtering out an insoluble matter, the reaction solution was distilled under reduced pressure to obtain 4.02 g of residue (crude yield; 99%). The obtained solid material was recrystallized with ethanol to obtain 3.85 g of

7-allyloxycoumarin compound (yield; 95%). The following analysis data of the obtained compound were obtained.

[00110] ^{1}H NMR ($CDCl_3$, 400 MHz): 4.60 (d, 2H), 5.49 (dd, 1H), 6.0-6.08 (m, 1H), 6.24 (d, 1H), 6.85 (d, 1H), 6.86 (dd, 1H), 7.38 (d, 1H), 7.64 (d, 1H) ppm. Infrared spectrum (KBr method) (primary absorptions): 3082, 1726, 1615, 1285, 1228, 1128, 1127, 998, 843 cm^{-1}.

(3) PREPARATION OF 3-(7-COUMARILOXY) PROPYLTRIETHOXYSILANE

[00111] 2.02 g (10 mmol) of 7-allyloxycoumarin and 1.80 g (11 mmol) of triethoxysilane were dissolved in 50 mL of toluene, and dry nitrogen was blown thereinto for 10 minutes. Then, the obtained solution was added with 0.5 mL of catalyst solution (2 mM platinum-1,3-divinyl-1,1,3, 3-tetramethyldisiloxane complex solution in toluene), and reacted therewith at about 25°C for 20 hours. After the solvent (toluene) was removed through distillation under reduced pressure, the obtained oily product was dried under reduced pressure to obtain 3.45 g of a crude target material (crude yield 95%). This crude product was directly used in the next synthesis (Example 1-(4) described below). The following analysis data of the obtained compound were obtained.

[00112] ^{1}H NMR ($CDCl_3$, 400 MHz): 0.75 (dd, 2H), 1.23 (t, 9H), 1.80-1.95 (m, 2H), 3.78 (q, 6H), 4.00 (t, 2H), 6.23 (d, 1H), 6.80-6.90 (m, 2H), 7.35 (d, 1H), 7.63 (d, 1H) ppm,

[00113] ^{13}C NMR ($CDCl_3$, 99 MHz): 9.97, 18.39, 22.61, 58.12, 70.58, 101.22, 112.23, 112.73, 112.79, 128.56, 143.29, 155.71, 161.05, 162.16 ppm.

[00114] Infrared spectrum (KBr method) (primary absorptions): 2970, 1736, 1616, 1124, 1078 cm^{-1}.

(4) SYNTHESIS OF COUMARIN DERIVATIVE-DERIVED ORGANIC FUNCTIONAL GROUP-INTRODUCED MESOPOROUS SILICA

[00115] 2 g of the mesoporous silica prepared in above (1) was suspended in 20 mL of n-hexane. Then, the suspension was added with 0.2 g of 3-(7-coumariloxy) propyltriethoxysilane, and stirred at about 25°C for 30 minutes. After removing the solvent through distillation under reduced pressure at 80°C for 2 hours, the obtained material was vacuum-dried at 150°C for 12 hours. The template (surfactant) remaining in the obtained coumarin derivative-derived organic functional group-contained mesoporous silica was removed by refluxing therethrough 100 mL of ethanol containing 1 M hydrochloric acid at 80°C for 4 hours. Then, the supernatant liquid was removed, and the solid material was re-subjected to reflux treatment using the same ethanol solution. After repeating the reflux treatment three times, the solid material was filtered, sufficiently rinsed with ethanol, and then dried at 80°C for 12 hours. The results of gas chromatography, thermogravimetry, and elemental analysis proved that the template surfactant was completely removed.

(5) ON-OFF CONTROL OF CONTROLLED-RELEASE OF CHOLESTANE USING COUMARIN DERIVATIVE-DERIVED ORGANIC FUNCTIONAL GROUP-INTRODUCED MESOPOROUS SILICA

[00116] 1 g of coumarin derivative-derived organic functional group-introduced mesoporous silica was suspended at about 25°C for 24 hours in 20 mL of n-hexane solution containing 1 g of cholestane dissolved therein. The mesoporous silica was filtered, rinsed 5 times with n-hexane, and dried at 60°C for 12 hours. The amount of cholestane remaining in the mesoporous silica was calculated from the amount of cholestane in n-hexane used in

the rinsing. As a result, it was verified that 33.0% by weight of cholestane was incorporated in the mesoporous silica.

[00117] Using a high-pressure mercury lamp, the solid body itself of the cholestane-incorporated mesoporous silica was irradiated for 3 hours with ultraviolet light in which light components of less than 310 nm of wavelength is removed by a heat-resistant hard glass jacket. Then, the mesoporous silica was re-suspended in 20 mL of n-hexane, and sufficiently stirred at about 25°C for 24 hours. Subsequently, the solid material was filtered, and rinsed with a sufficient amount of n-hexane. All the filtered solution and the rinsing solutions were combined, and subjected to gas chromatography to determine the quantity of eluted cholestane. The detected cholestane was 6%. That is, 27% of cholestane was still left in the solid material.

[00118] The solid body of the mesoporous silica itself was irradiated for about 5 minutes with ultraviolet light having a wavelength of about 240 to 260 nm using a low-pressure mercury lamp with a silica glass housing. Then, the mesoporous silica was re-suspended in 20 mL of n-hexane, and sufficiently stirred at about 25°C for 48 hours. Subsequently, the solid material was filtered, and rinsed with a sufficient amount of n-hexane. The filtered solution and the rinsing solutions were combined, and subjected to gas chromatography to determine the quantity of eluted cholestane. The incorporated cholestane was 10%. That is, 17% of cholestane was eluted.

[COMPARATIVE EXAMPLE 1] CONTROLLED-RELEASE OF CHOLESTANE USING MESOPOROUS SILICA DEVOID OF DIMERIZABLE FUNCTIONAL GROUP

[00119] The surfactant was removed from the mesoporous silica obtained in Example 1-(1), using ethanol containing hydrochloric acid in the same manner as in

Example 1-(4). This mesoporous silica was suspended at about 25°C for 24 hours in 20 mL of n-hexane solution having 1 g of cholestane dissolved therein. The mesoporous silica was filtered, and rinsed 5 times with n-hexane. Then, the mesoporous silica was dried at 60°C for 12 hours.

[00120] After the cholestane was incorporated in the mesoporous silica in this manner, the mesoporous silica was re-suspended in 20 mL of n-hexane, and sufficiently stirred at about 25°C for 24 hours. Then, the solid material was filtered, and rinsed with another sufficient amount of n-hexane. The filtered solution and the rinsing solutions were combined, and subjected to gas chromatography to determine the quantity of the eluted cholestane. Most of the initial cholestane was eluted in n-hexane, and the amount of the remaining cholestane was 2% or less.

[COMPARATIVE EXAMPLE 2] CONTROLLED-RELEASE OF CHOLESTANE USING COUMARIN DERIVATIVE-DERIVED ORGANIC FUNCTIONAL GROUP-INTRODUCED MESOPOROUS SILICA WITHOUT LIGHT IRRADIATION

[00121] The coumarin derivative-derived organic functional group-introduced mesoporous silica obtained in Example 1-(4) was suspended in 20 mL of n-hexane solution having 1 g of cholestane dissolved therein, at about 25°C for 24 hours. The mesoporous silica was filtered, and rinsed 5 times with n-hexane. Then, the mesoporous silica was dried at 60°C for 12 hours.

[00122] Without ultraviolet irradiation, the mesoporous silica was directly suspended in 20 mL of n-hexane, and sufficiently stirred at about 25°C for 24 hours. Then, the solid material was filtered, and rinsed with sufficient amount of n-hexane. The filtered solution and the rinsing solutions were combined, and subjected to gas chromatography to

determine the quantity of the eluted cholestane. Most of the initial cholestane was eluted in n-hexane, and the amount of the remaining cholestane was 2% or less.

[EXAMPLE 2] ON-OFF CONTROL OF CONTROLLED RELEASE OF PYRENE USING COUMARIN DERIVATIVE-DERIVED ORGANIC FUNCTIONAL GROUP-INTRODUCED MESOPOROUS SILICA

[00123] The controlled release of a functional substance was on-off controlled in the same manner as that in Example 1 except that 1 g of pyrene was used as a substance to be incorporated as a substitute for cholestane. After the mesoporous silica is irradiated with ultraviolet light using a high-pressure mercury lamp, and rinsed with n-hexane, 1.05% (by weight) of pyrene was incorporated in the mesoporous silica on the basis of 100% of the mesoporous silica. After the mesoporous silica is irradiated using a low-pressure mercury lamp, and rinsed with n-hexane, 0.28% (by weight) of pyrene was incorporated in the mesoporous silica on the basis of 100% of the mesoporous silica.

[00124] Comparative tests were conducted in the same manner as that in Comparative Examples 1 and 2 except that 1 g of pyrene was used as a substance to be incorporated as a substitute for cholestane. In either test, after the mesoporous silica was rinsed with n-hexane, 0.00% of pyrene was incorporated in the mesoporous silica.

[00125] As seen in the results of Examples 1, 2 and Comparative Examples, when the dimerizable organic group is photo-dimerized with ultraviolet irradiation, the incorporated functional substance (cholestane and pyrene) will not be controllably released even if the mesoporous silica is rinsed with a solvent for the functional substance. On the other hand, the incorporated functional substance (cholestane and pyrene) can be controllably released by irradiating the mesoporous silica with ultraviolet light of a shorter

wavelength and monomerizing the dimerized organic group. That is, the controlled-release of the incorporated substance could be on-off controlled by use of light. In particular, coumarin can be reversibly dimerized in response to light, which desirably allows the on-off control function to be repeated.

[00126] Although the invention has been described with respect to specific embodiments, the details are not to be construed as limitations, for it will become apparent that various embodiments, changes and modifications may be resorted to without departing from the spirit and scope thereof, and it is understood that such equivalent embodiments are intended to be included within the scope of this invention.